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by

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ABSTRACT

The $0/0_2$ concentration ratios above 100 km have been combined with knowledge of reaction and diffusion rates to construct a model of the neutral atmosphere between 80 and 120 km. The average eddy diffusion coefficient is determined within narrow limits by oxygen dissociation and recombination rates and by continuity requirements. The value of the eddy diffusion coefficient compatible with recent mass-spectrometer measurements is about 4×10^6 $cm^2 sec^{-1}$.

1. Introduction

The constituents of the earth's atmosphere are frequently considered to be in diffusive equilibrium above some altitude near 110 km, and in a well-mixed state at lower altitudes, i.e. mixing processes are considered to predominate over molecular diffusion below this altitude, but molecular diffusion to predominate over mixing at higher altitudes. Quantitative values for the mixing rates have normally not been mentioned in connection with such generalizations, but implicit in this assumption is the fact that the eddy diffusion coefficient must be approximately equal to molecular diffusion coefficients between 105 and 120 km and therefore have a value between 10^6 to 10^7 cm^2 sec^{-1}.

A more precise determination of the importance of eddy mixing is obtained from the continuity relationships for atomic and molecular oxygen when photodissociation and recombination processes are considered. Important amounts of molecular oxygen are dissociated at altitudes that are too high for recombination to occur at the same altitude. Laboratory data are available for molecular oxygen absorption coefficients and for the rates at which various recombination processes proceed. In addition the intensity of solar ultraviolet radiation has been measured in rockets. It is clear from examination of these physical constants and available data on atomic oxygen that recombination cannot occur at the same rate as dissociation above about 95 km. Therefore a downward transport of atomic oxygen must exist to allow recombination in a higher density region of the atmosphere. This downward transport of atomic oxygen (and upward transport of molecular oxygen) over the earth as a whole can only be brought about by eddy mixing processes, and the O/O_2 concentration ratio at the higher altitudes is controlled in part by the eddy mixing rates. Above 120 km, the molecular and atomic oxygen distributions must be almost in diffusive equilibrium (Nicolet and Mange, 1954), but their concentration ratio above 120 km will be affected by the rate of eddy mixing at lower altitudes. Below 80 km the atomic oxygen concentration must approach local photochemical equilibrium and not be greatly influenced by eddy transport.

It is the purpose of this paper to show that recent measurements of the O/O_2 concentration ratio above 120 km (Nier et al., 1964; Schaefer and Nichols, 1964) can be combined with knowledge of dissociation, recombination, and molecular diffusion rates to determine an average rate for eddy diffusion and to produce an atmospheric model for the lower thermosphere that possesses a degree of self-consistency not present in earlier models. The method consists of integrating the diffusion equations downward beginning at 120-km altitude under the assumption that the eddy diffusion coefficient is independent of altitude. The solution is constrained by the requirement that the eddy diffusion coefficient have the proper value to satisfy the continuity requirements for molecular and atomic oxygen.

2. Diffusion Equations

Throughout this paper, O, O_2, and N_2 will be identified by the subscripts 1, 2, and 3, respectively. In the region of interest, atomic and molecular oxygen will be considered to be diffusing through a stationary molecular nitrogen atmosphere; that is, there is assumed to be no net upward or downward flow of nitrogen. If there is no source or sink of O or O_2 other than photodissociation and recombination, the downward flux of atomic oxygen will be just twice the upward flux of molecular oxygen.

Before introducing eddy diffusion, it would be useful to consider the effect of these assumptions upon the equation for an atmosphere in diffusive equilibrium. For a multicomponent atmosphere, when mixing is neglected, the equation for the steady-state concentration gradient of the i^{th} constituent is (Chapman and Cowling, 1952)

$$\frac{dn_i}{dz} = -\frac{n_i}{H_i} - \frac{n_i}{T}\frac{dT}{dz} + \sum_{j \neq i} \frac{n_i \phi_j - n_j \phi_i}{ND_{ij}} \quad , \tag{1}$$

where D_{ij} is a mutual diffusion coefficient, N is the total particle concentration, T is the absolute temperature, and H_i and ϕ_i are the scale height and vertical flux of the i^{th} constituent. The steady state concentration gradient of nitrogen is then

$$\frac{dn_3}{dz} = -\frac{n_3}{H_3} - \frac{n_3}{T}\frac{dT}{dz} + \frac{n_3 \phi_1}{ND_{13}} + \frac{n_3 \phi_2}{ND_{23}} \quad . \tag{2}$$

The last two terms are small relative to n_3/H_3, and in addition ϕ_1 is of opposite sign to ϕ_2. Therefore it will be assumed to first order that the nitrogen concentration gradient is undisturbed by the two oppositely directed flows of O and O_2. The equations for the O and O_2 concentration gradients may be written

$$\frac{dn_1}{dz} = -\frac{n_1}{H_1} - \frac{n_1}{T}\frac{dT}{dz} - \frac{\phi_1}{D_1'} \tag{3}$$

and

$$\frac{dn_2}{dz} = -\frac{n_2}{H_2} - \frac{n_2}{T}\frac{dT}{dz} - \frac{\phi_2}{D_2'} \quad , \tag{4}$$

where the two "average" diffusion coefficients D_1' and D_2' have been defined as

$$D_1' = ND_{13}/(n_1 D_{13}/2D_{12} + n_2\, D_{13}/D_{12} + n_3) \tag{5}$$

and

$$D_2' = ND_{23}/(n_1 D_{23}/D_{12} + 2n_2\, D_{23}/D_{12} + n_3) \tag{6}$$

The fundamental equation of atmospheric diffusion has been modified by Lettau (1951) to include the effects of eddy diffusion. If winds and inertial effects due to motion of the air are neglected, the expression for the concentration gradient derived from Lettau's flux equation may be arrived at simply, although in a less rigorous manner, by considering the flux of the i^{th} component to be composed of two parts,

$$\phi_i = - D_i' \left\{ \frac{dn_i}{dz} + \frac{n_i}{H_i} + \frac{n_i}{T}\frac{dT}{dz} \right\} - K \left\{ \frac{dn_i}{dz} + \frac{n_i}{H_{ave}} + \frac{n_i}{T}\frac{dT}{dz} \right\} \tag{7}$$

where H_{ave} is the scale height of the mixed atmosphere. The first expression on the right represents the flux due to molecular diffusion, according to Eq. (3) or (4). In the absence of eddy mixing, this flow would continue until the gas is in diffusive equilibrium. The second expression, which includes K, the eddy diffusion coefficient, represents the net flow of the i^{th} constituent due to eddy diffusive mixing; the flux will be zero only when the i^{th} gas is distributed as in a completely mixed atmosphere. The equations for the vertical concentration gradients of atomic and molecular oxygen including both eddy and molecular diffusion are thus given by

$$\frac{dn_1}{dz} = -\frac{n_1}{D_1'+K}\left\{\frac{D_1'}{H_1} + \frac{K}{H_{ave}}\right\} - \frac{n_1}{T}\frac{dT}{dz} - \frac{\phi_1}{D_1'+K} \tag{8}$$

$$\frac{dn_2}{dz} = -\frac{n_2}{D_2'+K}\left\{\frac{D_2'}{H_2} + \frac{K}{H_{ave}}\right\} - \frac{n_2}{T}\frac{dT}{dz} - \frac{\phi_2}{D_2'+K} \tag{9}$$

The mutual diffusion coefficient for oxygen and nitrogen is given by $D_{23} = 0.181\ (T/T_o)^{1.75}\ (p_o/p)$, where T_o and p_o are standard temperature and pressure (Chapman and Cowling, 1952). The coefficients D_{12} and D_{13} for atomic oxygen through molecular oxygen and nitrogen are assumed in this calculation to be identical and equal to $0.26\ (T/T_o)^{1.75}\ (p_o/p)$. This number is taken from the experimental measurements of the diffusion of O through O_2 by Walker (1960) and is in good agreement with an extrapolation of the high temperature theory of Yun et al. (1962). The mutual diffusion coefficient of O and N_2 has not been measured, but was arbitrarily given the same value as the O and O_2 coefficient; the justification for this choice is simply that the high temperature collision integrals calculated by Yun and Mason (1962) for O - N_2 appear to closely resemble those of N - N_2, which in turn give a high temperature diffusion coefficient very close to the value for O - O_2. In addition, the measured value of the mutual diffusion coefficient for N and N_2 at 300° K by Young (1961) is close to that for O and O_2.

Table 1 gives the temperature profile and the nitrogen concentrations that were used in the calculations. Below 100 km, the values are taken from the U. S. Standard Atmosphere 1962, while at higher altitudes, they are taken from the Satellite Environment Handbook, 2nd ed. (Johnson, 1965).

3. The Continuity Equations

Two additional equations describe the variation in the flux of O and O_2 due to dissociation and recombination. At zero optical depth, the photodissociative lifetime of molecular oxygen is several days; below 100 km, this time becomes considerably longer. Similarly the eddy diffusion time constant $\tau \simeq H^2/K$ is approximately one day near 100 km if K is of the order of 5×10^6 cm^2 sec^{-1}. This value for K is consistent with the result of the present calculations. Because of these considerations and the expected long recombination lifetime of atomic oxygen in these regions, it is probably justifiable to assume that diurnal variations (at least above 90 km) can be ignored to a first order approximation. Significant time variations in atmospheric composition could take place in this region if K were to assume values of 10^8 cm^2 sec^{-1} or larger for even a fairly short time. No time dependence is considered in these calculations, however, and only an average value of K will be derived. The average flux and concentration of O and O_2 will also be determined in terms of an average value (over a complete day) for the photodissociation rate. For the low and middle latitude region considered here this average photodissociation rate is taken to be J/2, where J is the dissociation rate at a given altitude. The variation of J with altitude is derived from the computed values for the O_2 distribution and the solar ultraviolet spectral irradiance; it is discussed in the next section.

For most of the calculations only one recombination mechanism, the three-body recombination $O + O + M \rightarrow O_2 + M$, will be considered. The reaction $O + O_2 + M \rightarrow O_3 + M$ followed by various reactions involving the ozone may contribute significantly to recombination, particularly at night below 90 km. These reactions were ignored because the rate coefficients reviewed by Barth (1964) were small relative to direct recombination. It was called to our attention by

T. M. Donahue (private communication) that more recent experiments indicate a rate coefficient for the formation of ozone as much as an order of magnitude greater than previous values, making this an important recombination mechanism. Such reactions will have only a very small effect upon the calculation of the eddy diffusion coefficient since the required transport in this region is determined primarily by the dissociation rate of molecular oxygen at higher altitudes and not by the recombination mechanism. However the concentration of atomic oxygen will fall off somewhat more rapidly below 90 km.

If the coefficient for recombination of oxygen in the three-body collision process is α, the steady state continuity equations may be written

$$d\phi_1/dz = 2(J/2)n_2 - 2\alpha N n_1^2 \tag{10}$$

and

$$d\phi_2/dz = -(J/2)n_2 + \alpha N n_1^2 \tag{11}$$

which satisfy the condition $\phi_1 = -2\phi_2$.

4. Boundary Conditions and Solution.

Equations (8) to (11) can be integrated numerically from 120 km downward for a given temperature profile and corresponding nitrogen concentrations. The procedure is to assume initial values for n_1 and n_2 at 120 km and find a value of K that yields reasonable concentrations of O and O_2 at lower levels. In practice, the calculations were run down to 65 km, and n_1 and ϕ_2 were required to be greater than zero at this level. This condition was sufficiently stringent to allow only a very narrow range of values for K (<1%) for each assumed n_1/n_2 (O/O_2 concentration ratio) at 120 km. The value of n_2 chosen at 120 km was constrained by a further requirement that, at 80 km, n_2 was to be 20.97 $\pm$ 0.10 percent of the total number density. The initial value of ϕ_2 to be used in this computation was determined by a separate calculation; equations (9) to (11) were integrated upward from 120 km and an initial value of the flux was found which resulted in reasonable values of atomic and molecular oxygen above 200 km. The value of ϕ_2 obtained was always near that expected for the O_2 concentration and photodissociation rate at 120 km, $\phi_2 \cong (J/2)n_2H_2$. An iterative procedure using the previously described downward integration was used to obtain a correct K for this integration.

The photodissociation rate J and its variation with altitude are of central importance in this problem. The values used in this work were obtained by calculating the number of photons absorbed per second in 50 Å intervals in the Schumann-Runge continuum from 1175 Å to 1775 Å. The oxygen absorption spectrum was taken from the measurements of Watanabe et al. (1953) and Metzger and Cook (1964) and the solar emission spectrum was that of Detwiler et al. (1961). By treating each 50 Å interval separately, J could be found as a function of column density of O_2, as shown in Fig. 1. The dotted portion of the curve represents an interpolation between the dissociation coefficient calculated for Schumann-Runge absorption and the value of this coefficient in the Herzberg continuum. In order to calculate J for column densities in this range it would be necessary to know what portion of the energy absorbed in the Schumann-Runge bands results in dissociation. However, the results of the present calculations are quite insensitive to the shape of the absorption curve for column densities greater than 10^{19} O_2 molecules/cm^2; i.e. oxygen dissociation above 80 km is due almost entirely to radiation in the Schumann-Runge continuum. The values of J used in Eqs. (10) and (11) were obtained for each step of the integration from computed O_2 column densities. The column density of O_2 was calculated assuming an "average" slant path angle of 45° to the vertical. This angle was chosen to give approximately the correct average number of dissociations per day in the 80 to 120 km region. This approximation appears to be reasonable since neglect of the slant path (zero degree slant path angle) results in an over-estimate of the eddy diffusion coefficient by 25 per cent and the atomic oxygen at 80 km by about 20 per cent.

The recombination coefficient for the process, $O + O + M = O_2 + M$, where M represents any atmospheric constituent, was taken to be $\alpha = 2.6 \times 10^{-34}\ T^{1/2}\ cm^6\ sec^{-1}$. This coefficient was obtained by adding a temperature dependence to the value measured by Marshall (1962).

5. Results and Discussion

Figure 2 illustrates the convergence of several attempted solutions toward the value of K which satisfies the lower boundary conditions, i.e., that n_1 and ϕ_2 should both be positive. These two quantities behave oppositely as the integration is extended to lower altitudes, thus when n_1 begins to increase sharply, ϕ_2 very rapidly becomes negative, and vice versa. For clarity only n_1 has been plotted in Fig. 2. The computations were performed down to 65 km and are plotted down to 70 km, but the validity of the results for the atomic oxygen concentration is probably questionable below about 85 km.

The atmospheric composition for several different n_1/n_2 ratios at 120 km, together with their unique values of K, are shown in Fig. 3. The downward fluxes of atomic oxygen which correspond to each of these cases are plotted in Fig. 4. It follows from the continuity equation that the atomic oxygen concentrations cross the chemical equilibrium curve at the altitude at which the flux is a maximum. This excess downward flow of atomic oxygen, which at these heights is transported almost entirely by eddy diffusion, results in an increase of atomic oxygen above its photochemical equilibrium value below this crossing altitude. The excess is consumed at lower altitudes and finally the curves will all approach photochemical equilibrium. At the altitude where this takes place, however, considerably more chemistry must be included to yield a proper analysis.

The measurements of Nier et al. (1964), Schaefer and Nichols (1964), and Pokhunkov (1964) indicate that the concentrations of atomic and molecular oxygen are very nearly equal at 120 km. These measurements coupled with our calculations indicate that the average eddy diffusion coefficient should be about 4×10^6 cm^2 sec^{-1}.

A plot of the eddy diffusion coefficient as a function of the n_1/n_2 ratio at 120 km is shown in Fig. 5. It is a peculiar fact that K is very nearly inversely related to this ratio by the equation

$$K(n_1/n_2)_{120\ \mathrm{km}} = 4 \times 10^6\ \mathrm{cm}^2\ \mathrm{sec}^{-1} \qquad (12)$$

Other estimates of the eddy diffusion coefficient have been given based on the direct observation of chemical releases in the atmosphere. Hines (1963) gives a value of the order of 10^6 cm^2 sec^{-1} while Zimmerman and Champion (1963) find values near 90 km from 2×10^6 cm^2 sec^{-1} up to 10^8 cm^2 sec^{-1}. The values of K obtained in this manner have been derived in rather short time intervals near sunrise and sunset, but still are in fair agreement with the average value found here.

A theoretical upper limit on the average value of K can be derived using a method due to Johnson and Wilkins (1965). The limit is based upon the idea that the heat flux F transported downward by turbulent mixing cannot exceed the total heat absorbed in the atmosphere at all higher levels. The predominant heat source is the radiation absorbed by molecular oxygen in the Schumann-Runge continuum. In their calculations, Johnson and Wilkins assumed that above 95 km only 20 percent of the absorbed radiation appeared as heat. This would be reasonable if all of the energy in the excited oxygen atom $O(^1D)$ were radiated, but the fraction of the absorbed solar energy appearing as heat could be as high as 40 percent if de-excitation occurred primarily by collision with N_2,

$$O(^1D) + N_2 \rightarrow O(^3P) + N_2^* + K.E. \quad , \qquad (13)$$

followed by collisional de-excitation of the vibrationally excited N_2 (DeMore and Raper, 1964). S. P. Zimmerman (private communication) has pointed out that the expression for the upper limit on the average value of K given by Johnson and Wilkins should be corrected to read

$$K = -F(\rho c_p T d\ln\theta/dz)^{-1} \qquad (14)$$

where c_p is the specific heat at constant pressure, ρ is the atmospheric density, and θ is the potential temperature. If it is assumed that all the $O(^1D)$ energy becomes available as heat energy, equation (14) yields an upper limit of $K \simeq 10^7$ cm^2 sec^{-1} at 100 km (for the same Schumann-Runge fluxes used elsewhere in this paper). This value is twice as great as the average value for K compatible with the mass-spectrometer data. The discrepancy, if real, would imply that the energy lost by radiation from this region is comparable to that conducted downward by eddy diffusion. More likely the difference is due to the uncertainty in our knowledge of the various atmospheric parameters which enter these calculations.

It is quite likely that the eddy diffusion coefficient is a function of altitude, so that the assumption here of a constant coefficient with altitude is inadequate. A calculation was made in which K was constant below 100 km and rose linearly between 100 km and 120 km to a value one order of magnitude larger. The change in distribution of atomic oxygen is shown in Fig. 6 for an n_1/n_2 ratio of 2 at 120 km. While there is no evidence to recommend this particular variation in K its value in the 80 km to 100 km region was reduced to 8.5×10^5 $cm^2 sec^{-1}$ compared to the average value of 2.0×10^6 $cm^2 sec^{-1}$ for the same case with constant K.

Since use is sometimes made of the relative abundance of oxygen to nitrogen, the ratio $(n_1 + 2n_2)/2n_3$ is shown in Fig. 7 for each of the assumed

n_1/n_2 ratios at 120 km and the corresponding eddy diffusion coefficients. The values above 120 km were obtained by an upward integration of Eqs. (1) - (4) using the temperature profile of the medium density atmosphere given in the Satellite Environment Handbook, 2nd ed. (Johnson, 1965). The large effect of different mixing rates below 120 km on this ratio in the diffusively separated region can easily be seen in Fig. 7.

The decrease in the oxygen-to-nitrogen ratio just above 100 km appears to be real; it is apparently the consequence of the combined effects of molecular and eddy diffusion. In the altitude region where molecular and eddy transport of oxygen are of comparable importance, the eddy transport acts to move molecular oxygen upwards, but this tendency can be opposed by the molecular diffusion process (unless the molecular oxygen concentration falls off with altitude at a rate even faster than the diffusive equilibrium rate). The eddy transport acts to move atomic oxygen downward, and the molecular diffusion process always assists in this. The fact that the molecular diffusion can act to oppose the eddy diffusion of molecular oxygen upward, whereas the two always cooperate in transporting atomic oxygen downward, is probably responsible for the depletion of oxygen relative to nitrogen in the region just above 100 km. This effect is finally overcome, of course, by molecular diffusion coming to predominate over eddy diffusion at still higher altitudes.

Table 2 shows the effect upon K of changes in the physical constants used in the calculation. The atmospheric model for an n_1/n_2 ratio equal to 2.0 at 120 km was chosen as a standard, and each parameter was varied independently. As would be expected, the greatest changes occurred when the assumed solar radiation arriving at the top of the atmosphere was varied. The average eddy diffusion necessary to support a given n_1/n_2 ratio at 120 km increases or decreases slightly more than the fractional change in J.

The distribution of atomic and molecular oxygen for a given n_1/n_2 ratio at 120 km is not significantly affected by any reasonable change in the recombination rate except at the lowest altitudes. The values chosen for the direct three-body recombination coefficient in Table 2 cover the entire range of experimental and theoretical values discussed by Barth (1964).

As mentioned earlier the production of ozone may result in a somewhat lower concentration of atomic oxygen below 90 km, but the eddy diffusion coefficient is not significantly affected. The calculation was repeated with a recombination term $-2\beta\, n_1 n_2 N$ added to Eq. 10 and $\beta n_1 n_2 N$ added to Eq. 11. This is equivalent to the assumption that all ozone formed by the process $O + O_2 + M \rightarrow O_3 + M$ recombines in some fashion with atomic oxygen to form two oxygen molecules. Actually photodissociation of ozone will restore a large part of the atomic oxygen removed by the formation of ozone. The rate constant used, $\beta = 8.7 \times 10^{-35}\, T^{1/2}$, is the largest that has been proposed for this reaction. Even with these extreme assumptions the eddy diffusion coefficient calculated was only reduced from 2.02×10^6 cm^2 sec^{-1} to 1.92×10^6 cm^2 sec^{-1}. This calculation provides a lower limit for the atomic oxygen concentration which falls off much more rapidly below 90 km, as shown in Fig. 8. Also shown is the result of arbitrarily increasing the rate coefficient α by an order of magnitude.

The results are not very sensitive to the exact values of the diffusion coefficients, and only that of O-N_2 and O-O_2 might be seriously in error. However a diffusion coefficient differing by a factor of two from the value used does not alter the value of K by more than fifteen percent.

6. Conclusions

The ratios of atomic to molecular oxygen concentrations in the atmosphere above 120 km are closely related to the strength of eddy diffusion in the 80 to 120 km region. Measurement of the n_1/n_2 ratio therefore provides information about the eddy mixing rate in the highest part of the atmosphere in which eddy mixing is still important. While great precision cannot be claimed for calculations dealing with such fluctuating atmospheric properties as eddy mixing, the relationship between mixing and other atmospheric parameters has been clarified and realistic limits can be placed on average mixing rates.

The few available measurements of the n_1/n_2 ratio indicate a value near unity at 120 km. Even allowing for the possibility that recombination in the measuring instruments may cause a low measured value, the n_1/n_2 ratio almost surely falls between 0.5 and 5 at 120 km in the lower and middle latitudes. The average eddy diffusion coefficient in the 80 to 120 km altitude range must therefore have a value between 8×10^5 and 8×10^6 cm^2/sec. For reasonable values of K a rather broad peak in the atomic oxygen concentration is found near 90 km where the maximum concentration is within a factor of two of 5×10^{11} atoms cm^{-3}. The total column density of atomic oxygen is found to be of the order of 1.5×10^{18} atoms cm^{-2}.

The effects of large-scale circulation have not been taken into account. To the extent that the large-scale circulation contributes to the overall removal of atomic oxygen from, and supply of molecular oxygen to, the thermosphere, the eddy diffusion coefficients derived here should be reduced.

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TABLE 1

Atmospheric Parameters Used in the Evaluation
of Oxygen Transport in the Atmosphere

Altitude (km)	Temperature (^{o}K)	Nitrogen Concentration (cm^{-3})
120	295	4.04×10^{11}
115	262	8.07×10^{11}
110	240	1.62×10^{12}
105	224	3.52×10^{12}
100	210	8.20×10^{12}
95	196	1.99×10^{13}
90	181	5.20×10^{13}
85	181	1.30×10^{14}
80	181	3.28×10^{14}
75	200	7.11×10^{14}
70	220	1.44×10^{15}
65	239	2.74×10^{15}

TABLE 2

Effect on the Eddy Diffusion Coefficient of Changes in the Dissociation, Recombination, or Molecular Diffusion Rates

Dissociation Rate at Zero Optical Depth $J=5.6\times10^{-6}\,sec^{-1}$	Recombination Coefficient $O + O + M \rightarrow O_2 + M$ $\alpha=2.6\times10^{-34}T^{1/2}cm^6 sec^{-1}$	$O-O_2$ and $O-N_2$ Mutual Diffusion Coefficients $D_{12}\equiv D_{13}=0.26(T/T_o)^{1.75}(P_o/P)cm^2 sec^{-1}$	Eddy Diffusion Coefficient K in 10^6 cm^2/sec
J	α	D_{12}	2.02
2/3 J	α	D_{12}	1.21
1.5 J	α	D_{12}	3.27
J	1/2 α	D_{12}	2.01
J	2 α	D_{12}	1.98
J	α	1/2 D_{12}	2.26
J	α	2 D_{12}	1.74

Figure Captions

1. Photodissociation rate as a function of molecular oxygen column density. The dashed portion of the curve is an interpolation between values of absorption computed for the Schumann-Runge continuum and absorption in the Herzberg continuum.

2. Atomic oxygen concentrations for several values of the eddy diffusion coefficient, K. The numbers identifying each curve are values of K in units of $cm^2 sec^{-1}$. This figure illustrates the narrow range of acceptable K values for a given ratio of O to O_2 at 120 km.

3. Altitude dependence of atmospheric composition for several values of the atomic to molecular oxygen ratio at 120 km. The curve marked photochemical equilibrium indicates the atomic oxygen concentration that would be expected in the absence of vertical transport if the only sink for atomic oxygen were the reaction $O + O + M \rightarrow O_2 + M$.

4. Downward flux of atomic oxygen for the atomic to molecular oxygen ratios at 120 km of Figure 3.

5. Dependence of the average eddy diffusion coefficient above 80 km on the ratio of atomic to molecular oxygen at 120 km.

6. Comparison of atomic and molecular oxygen concentrations for two forms of the eddy diffusion coefficient, K. For the solid curve K = 2.02×10^6 cm^2/sec; for the dashed curve K changes by an order of magnitude between 100 and 120 km.

7. Ratio of the number of oxygen atoms to the number of nitrogen atoms for the various models discussed in the text. The numbers identifying the curves are the atomic to molecular oxygen ratios at 120 km.

8. The effect upon atomic oxygen concentration of much larger recombination rates than those used in these calculations. α is the three-body recombination coefficient for the formation of O_2 and β is the three-body recombination coefficient for the formation of O_3.

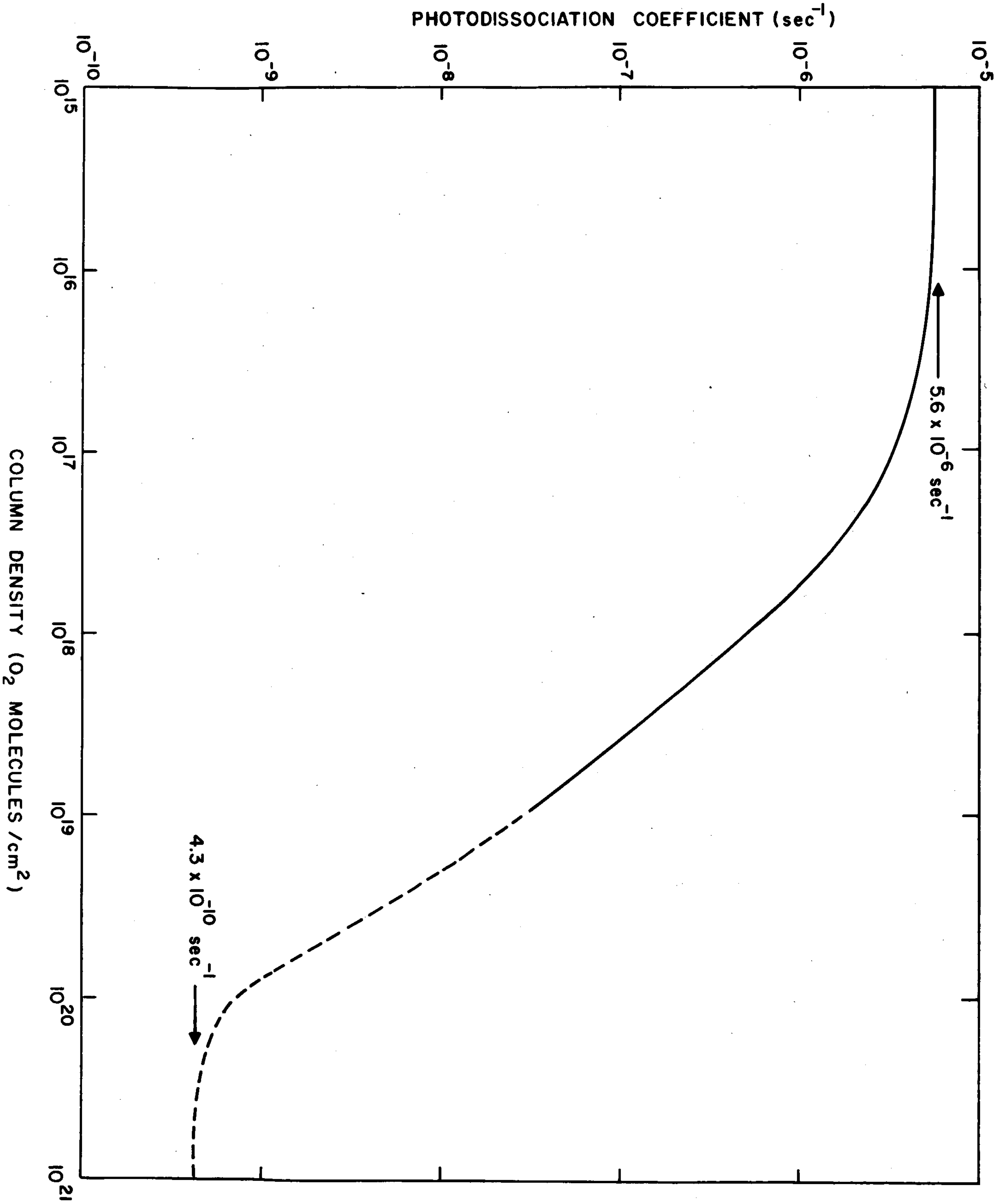
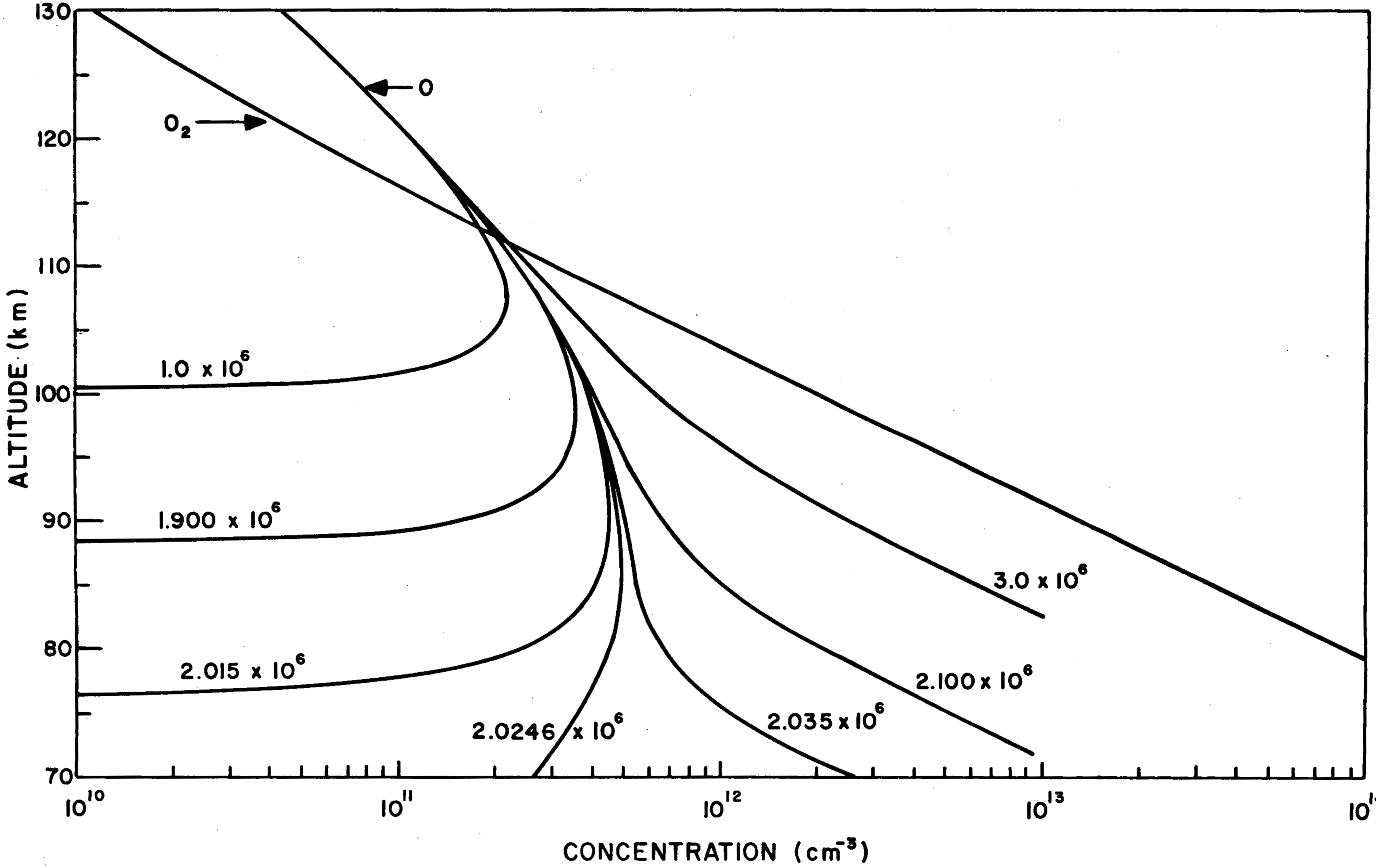
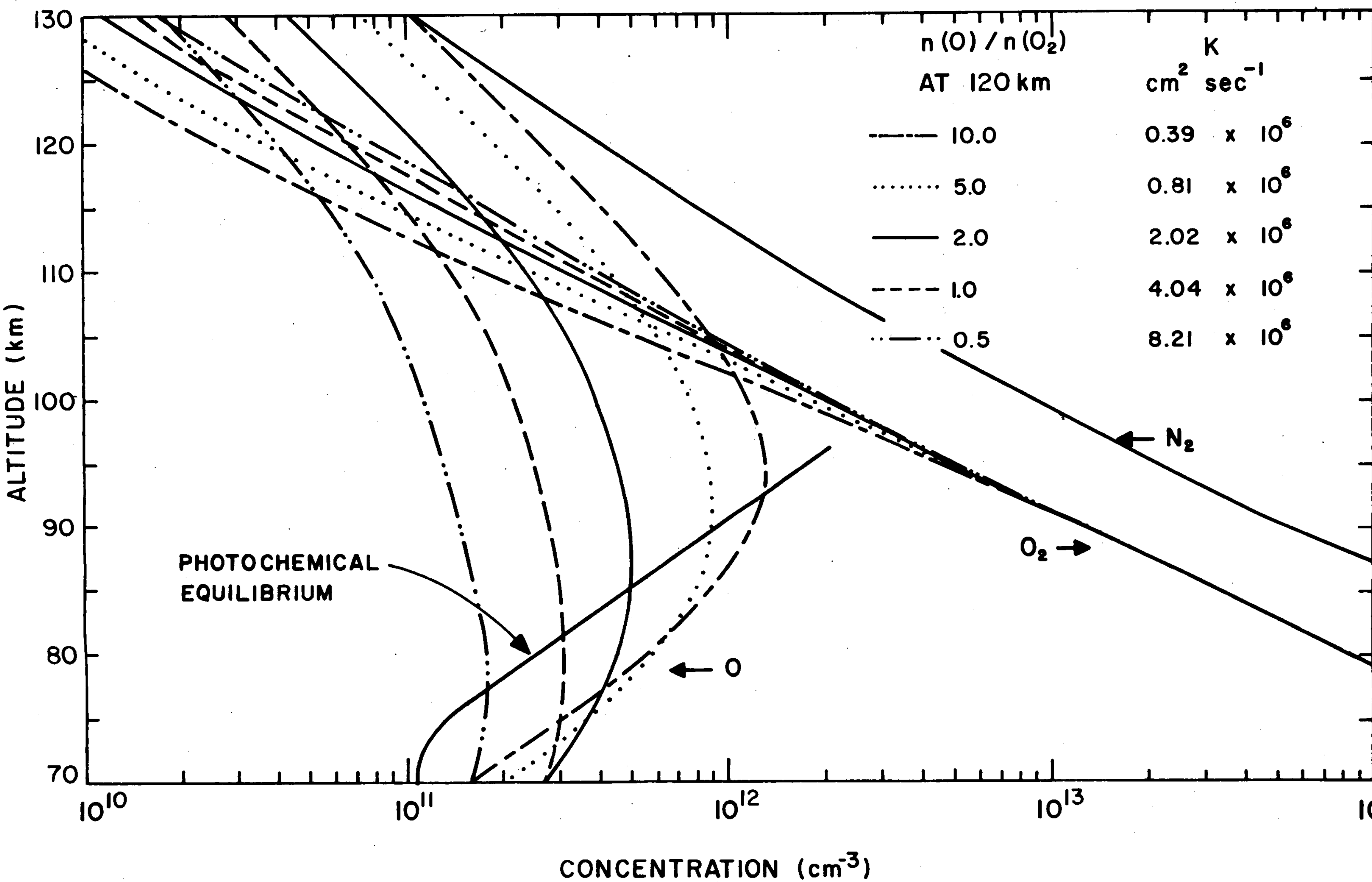

PHOTODISSOCIATION COEFFICIENT (sec^{-1})
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
5.6×10^{-6} sec^{-1}
4.3×10^{-10} sec^{-1}
COLUMN DENSITY (O_2 MOLECULES /cm^2)

FIGURE 1



ALTITUDE (km)
130
120
110
100
90
80
70
O_2
O
1.0×10^6
1.900×10^6
2.015×10^6
2.0246×10^6
2.035×10^6
2.100×10^6
3.0×10^6
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
CONCENTRATION (cm^{-3})

FIGURE 2



ALTITUDE (km)
130
120
110
100
90
80
70
CONCENTRATION (cm^{-3})
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
$n(O)/n(O_2)$ AT 120 km
K $cm^2\ sec^{-1}$
10.0 0.39 x 10^6
5.0 0.81 x 10^6
2.0 2.02 x 10^6
1.0 4.04 x 10^6
0.5 8.21 x 10^6
N_2
O_2
O
PHOTOCHEMICAL EQUILIBRIUM

FIGURE 3

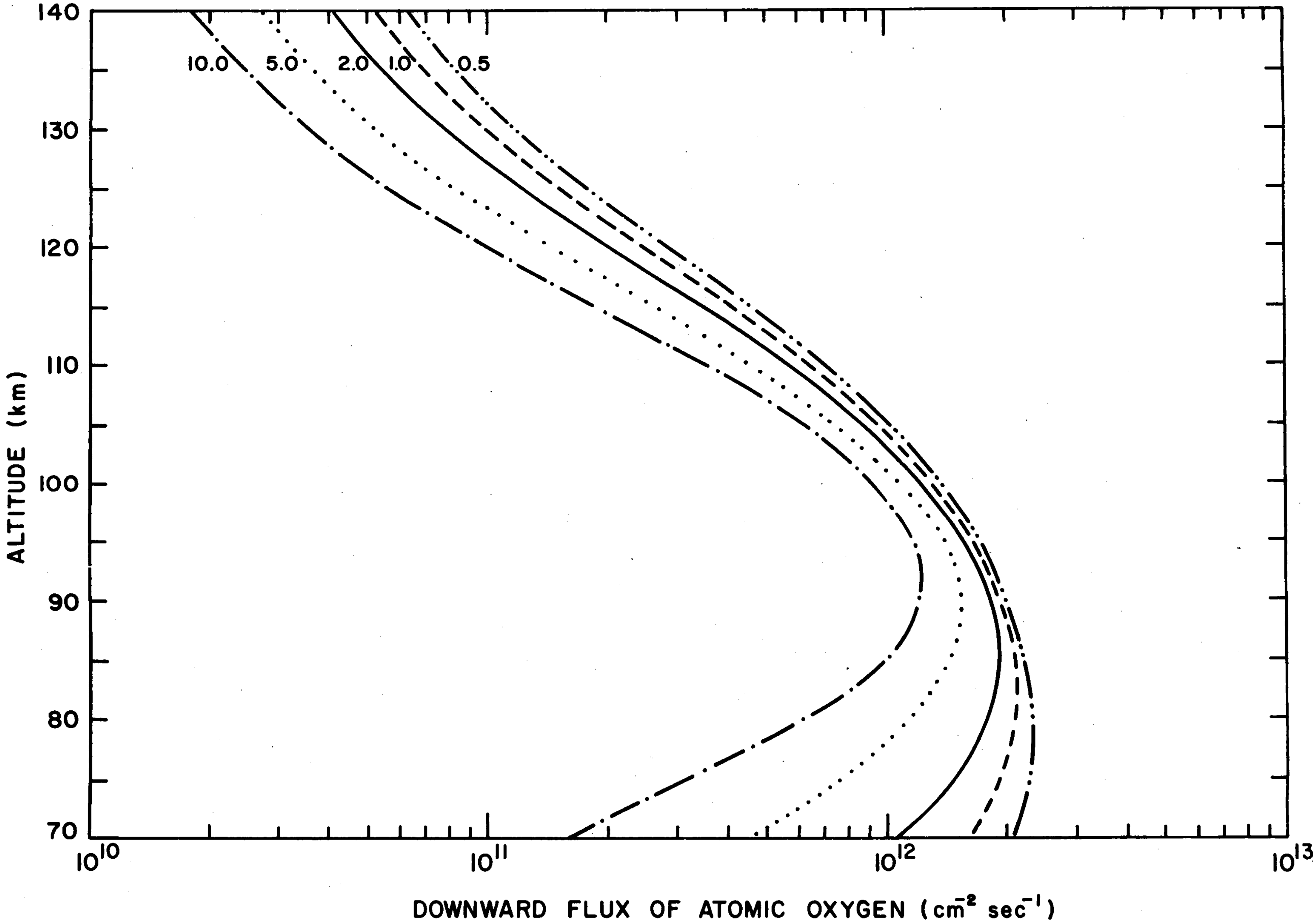

140
130
120
110
100
90
80
70
ALTITUDE (km)
10.0
5.0
2.0
1.0
0.5
10^{10}
10^{11}
10^{12}
10^{13}
DOWNWARD FLUX OF ATOMIC OXYGEN (cm^{-2} sec^{-1})

FIGURE 4

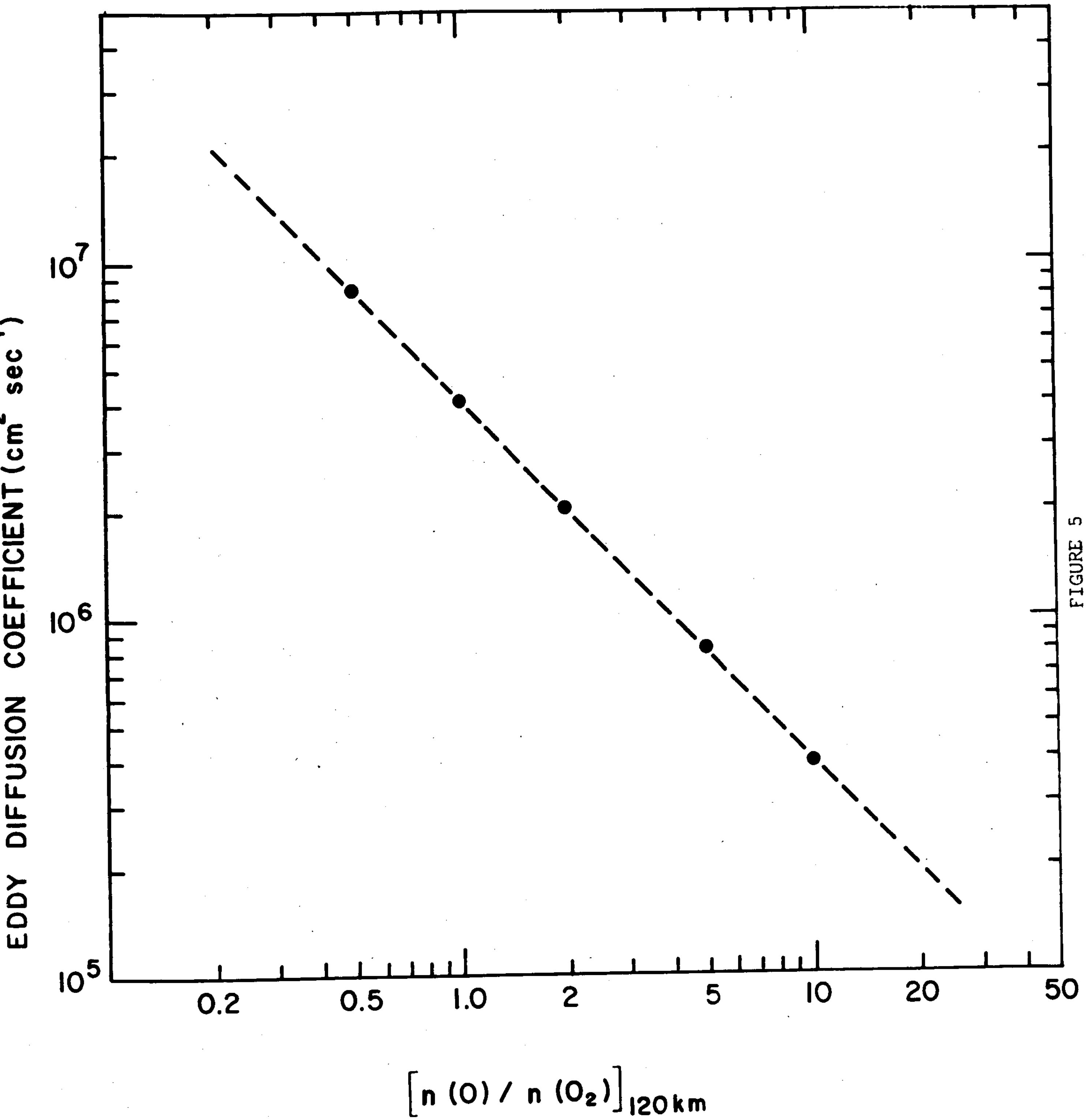

EDDY DIFFUSION COEFFICIENT (cm^2 sec^{-1})
10^7
10^6
10^5
0.2
0.5
1.0
2
5
10
20
50
[n (O) / n (O$_2$)]$_{120 km}$

FIGURE 5

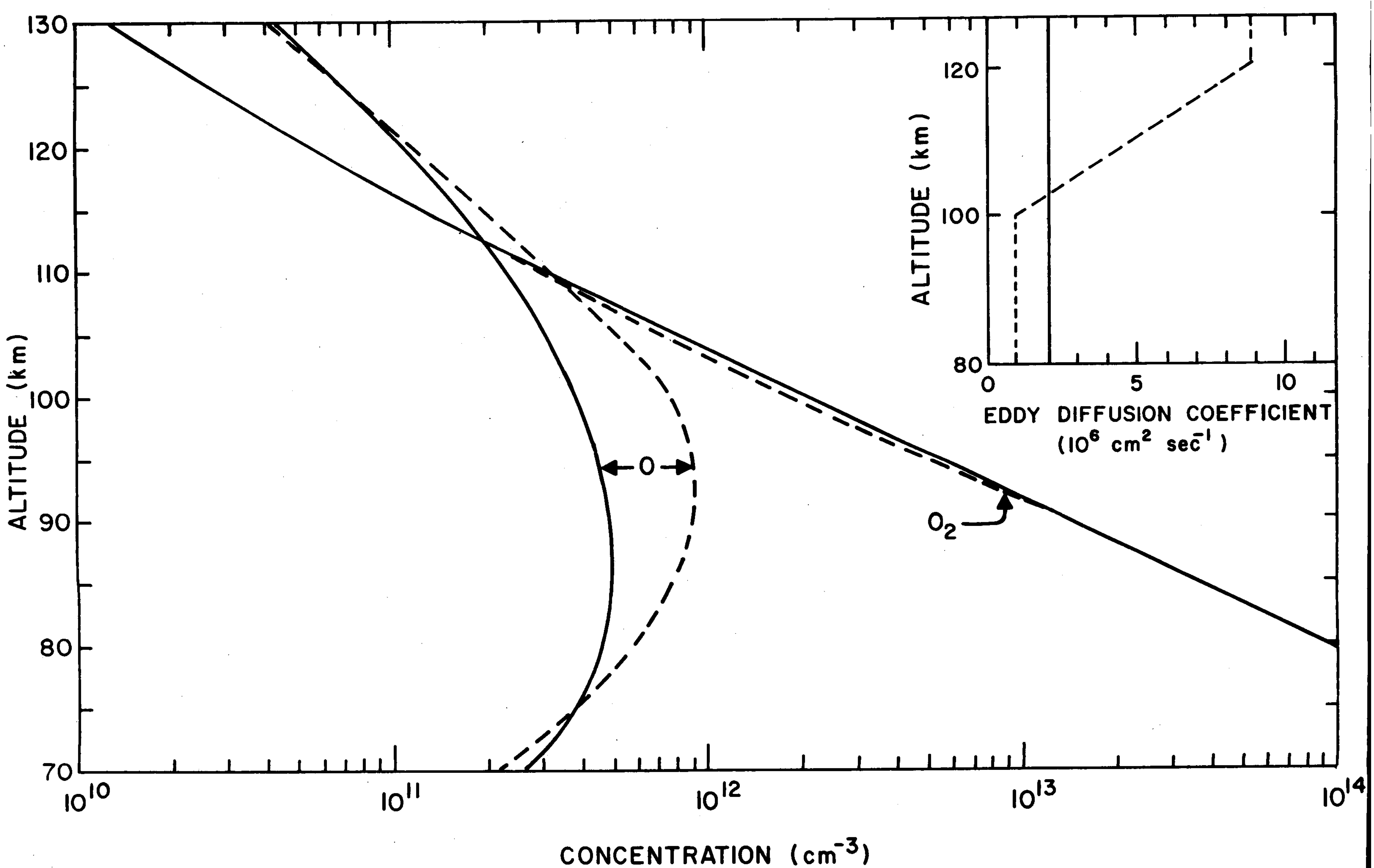

ALTITUDE (km)
130
120
110
100
90
80
70
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
CONCENTRATION (cm^{-3})
O
O_2
ALTITUDE (km)
120
100
80
0
5
10
EDDY DIFFUSION COEFFICIENT
(10^6 cm^2 sec^{-1})

FIGURE 6

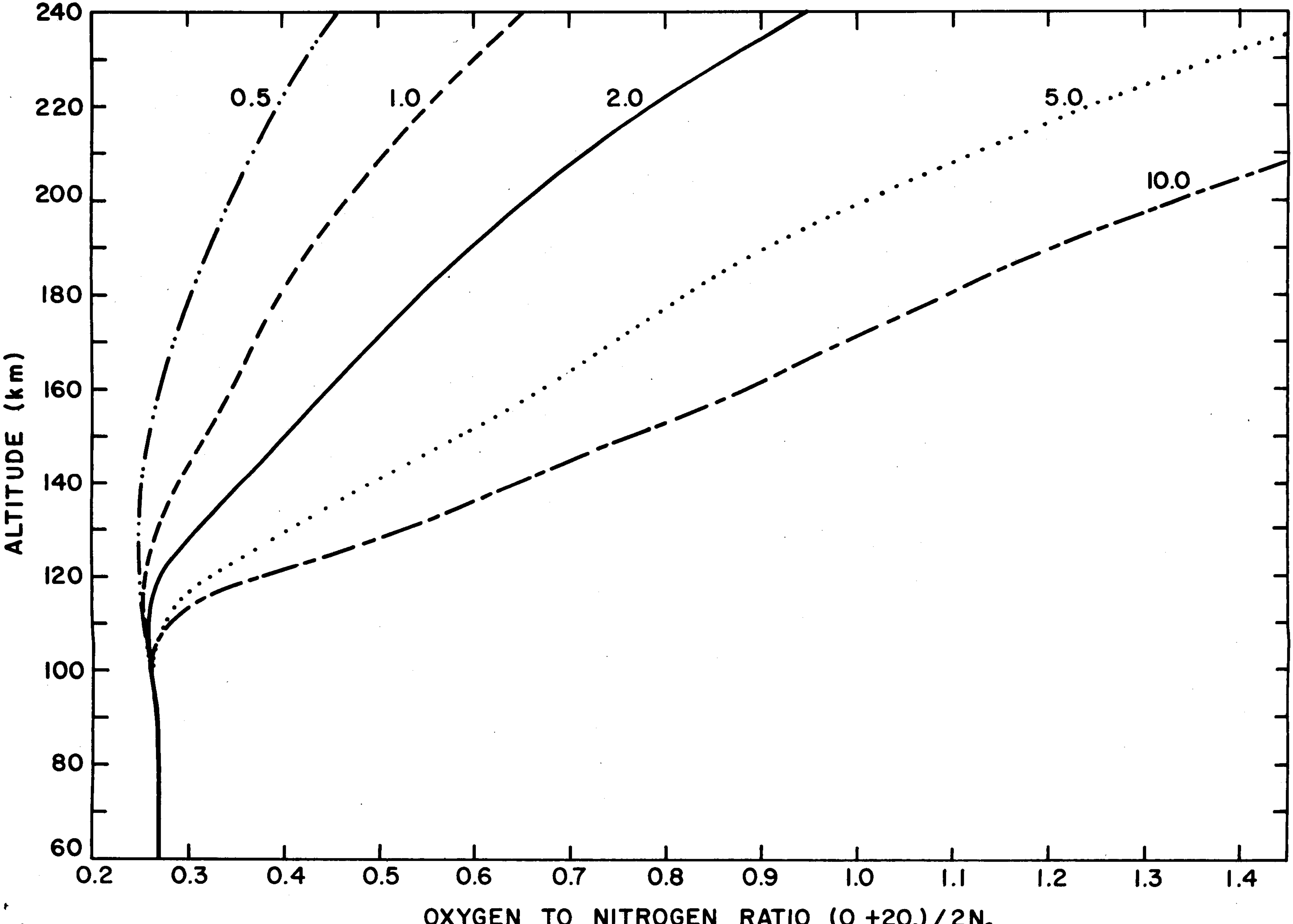
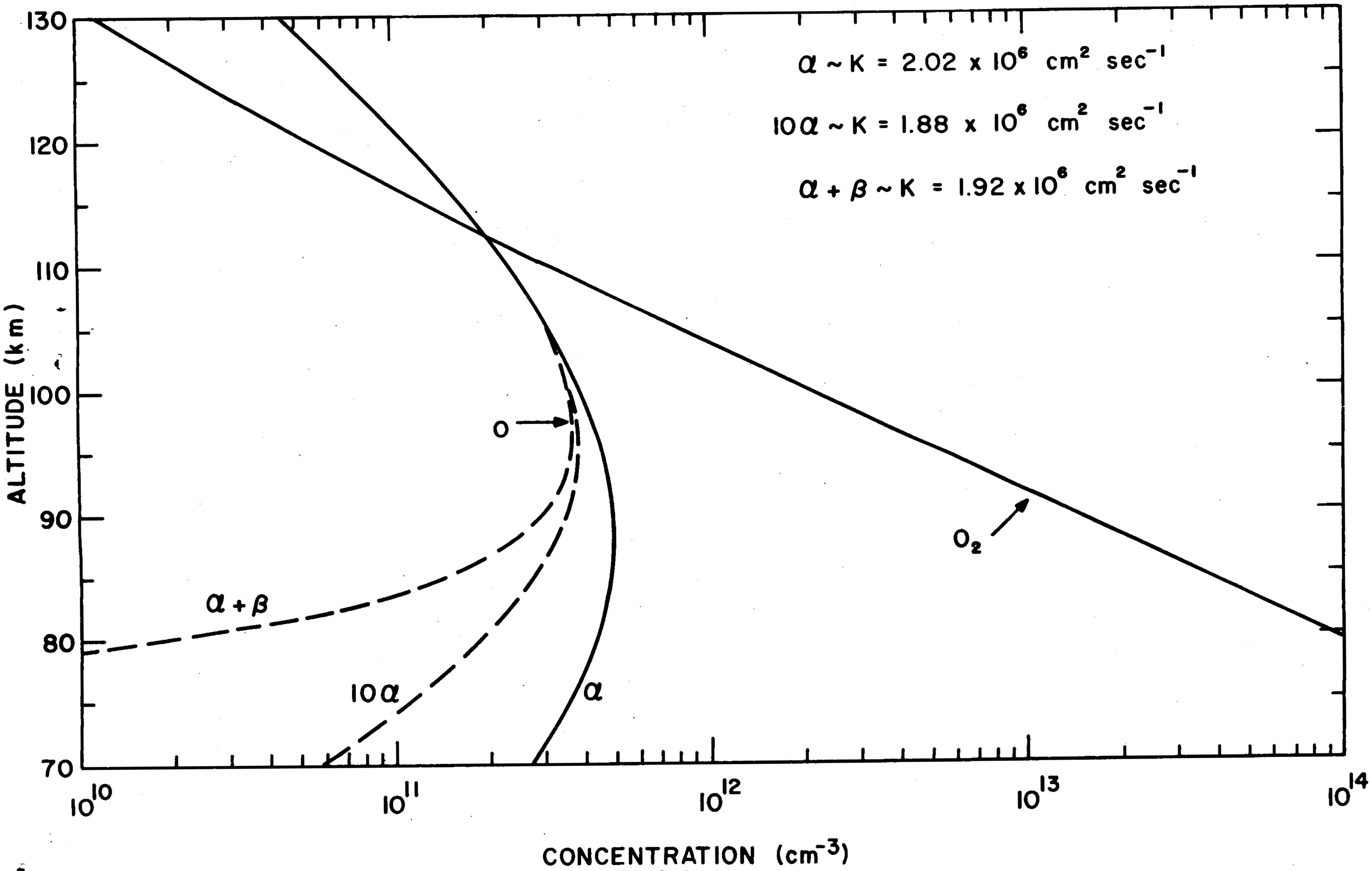

240
220
200
180
160
140
120
100
80
60
ALTITUDE (km)
0.5
1.0
2.0
5.0
10.0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
OXYGEN TO NITROGEN RATIO $(O + 2O_2)/2N_2$

FIGURE 7



ALTITUDE (km)
130
120
110
100
90
80
70
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
CONCENTRATION (cm^{-3})
$\alpha \sim K = 2.02 \times 10^6\ cm^2\ sec^{-1}$
$10\alpha \sim K = 1.88 \times 10^6\ cm^2\ sec^{-1}$
$\alpha + \beta \sim K = 1.92 \times 10^6\ cm^2\ sec^{-1}$
O
O_2
$\alpha + \beta$
10α
α

FIGURE 8